A Framework for Modeling In-Use Deterioration of Light-Duty Vehicle Emissions Using MOBILE6

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ABSTRACT

The U.S. Environmental Protection Agency is currently revising its Mobile Source Emission Factor Model, used to estimate the inventory of exhaust and evaporative emissions from on-road motor vehicles. This paper describes the framework used in calculating basic exhaust emission rates as a function of accumulated vehicle mileage. In general, these rates increase with mileage. In version 6 of the model, MOBILE6, vehicle exhaust emissions are separated for the first time into "start" and "running" components. This enables more precise descriptions in the model for specific types of driving. Basic rates for start and running emissions are estimated from laboratory test data and from state inspection and maintenance program data. The data suffer from various limitations, and considerable engineering judgment must be used to augment traditional statistical methods to arrive at practical results.

INTRODUCTION

The U.S. Environmental Protection Agency's (EPA) Mobile Source Emission Factor Model (MOBILE) is used by various groups in government and industry to obtain estimates of emissions from on-road

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vehicles. State, regional, and local governments combine output from the model with estimates of pollution from other sources to help develop air quality management plans. Vehicle and fuel manufacturers are concerned with the impact of the model's predictions on government policies that affect activities in their industries. By the same token, as part of their mission members of the environmental community monitor local developments with MOBILE.

This paper reports on the development of basic exhaust emission rates expressed as a function of vehicle mileage accumulation. In general, these rates increase with mileage. At the request of many of the model's users, vehicle exhaust emissions will be separated for the first time into "start" and "running" components in version 6 of MOBILE (MOBILE6). This will enable more precise descriptions of specific types of driving in the model. Basic rates for start and running emissions are estimated from laboratory test data and from state inspection and maintenance (I/M) program data. In most cases, while the quantity of data is large, they have been collected for some other primary purpose and are not ideally suited to the problem of estimating emissions deterioration. Therefore, considerable engineering judgment has been used to augment traditional statistical methods in arriving at practical results.

The following account is intended as a broad overview of the steps taken to arrive at model equations. It represents a synthesis of work described in more detail in a series of reports prepared by EPA as part of the current MOBILE revision project. Readers interested in these details are referred to supporting documents cited here and available at the EPA web site: www.epa.gov/OMSWWW/M6. In particular, statistical measures of uncertainty are largely omitted from this paper.

Most of the work discussed here deals with 1981 to 1993 model year light-duty cars and trucks. At the time of this writing, substantial new data were available only for this portion of the vehicle fleet. Treatment in MOBILE6 of other model years and vehicle classes is described briefly in the results section, with more complete details found in additional EPA reports.

MODELING BASIC EMISSION RATE DETERIORATION

EPA's study of in-use deterioration of exhaust hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions began as a broad analysis of how rates of emission change as a vehicle ages and accumulates mileage. Much of the early work involved problem definition and identification of useful data sources.[1] Over time, the in-use deterioration study merged with the ongoing MOBILE model revision in order to supply the latter with required input. This shift gave the analysis greater focus, while perhaps limiting its generality.

In MOBILE6, vehicle exhaust emissions will be allocated between engine start (start emissions) and travel (running emissions). This split enables the separate characterization of start and running emissions for correction factors such as fuel effects and ambient temperature. It also allows a more precise weighting of these two aspects of exhaust emissions for particular driving situations, such as those associated with morning commutes, parking lots, and freeways.

Traditional emissions testing does not directly reflect the start/running emission division, and this creates difficulties in the development of models using actual data. The accepted unit of emission measurement is a vehicle's recorded emissions, in grams per mile, on the Federal Test Procedure (FTP), a laboratory test designed to reflect real-world driving.[2] An FTP score is computed from the values of three "bags" of emissions. Bags one and three capture a combination of start and running emissions, while bag two measures running emissions alone. A large body of FTP data has been collected since the inception of the FTP protocol and is available from various sources. In order to utilize these data in the study of start and running emissions deterioration, it is necessary to develop a method of segregating the start and running components associated with given FTP test results.

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[1]For a more complete review, see Mobile Sources Technical Review Subcomittee (1997).

[2]In recognition that the FTP does not adequately represent more extreme levels of speed and acceleration, a "supplemental" FTP component will be included in future test programs. Data from this cycle were not available for the current study. See USEPA (1993) for complete details.

A second challenge involves addressing concerns over possible bias in FTP test results. Since the estimates of running emissions deterioration are based on FTP tests obtained from public vehicle recruitment programs, there is a concern that low vehicle recruitment rates in these programs may sustain sampling bias; typically less than 25% of drivers/owners asked to participate actually do so (Mobile Sources Technical Review Subcomittee 1997). Whether such a bias, if it exists, results in overestimation or underestimation of the true emissions deterioration is a matter of debate. Nonetheless, a method for overcoming this situation was included in the analysis described below. It utilizes data from state and inspection maintenance (I/M) programs based on the IM 240 test. This test is designed to produce emissions similar to the FTP over a shorter cycle more appropriate for the high volume of testing required in an I/M program (USEPA 1992).

DATA

Several data sets were needed ultimately to model deterioration of light-duty vehicle exhaust emissions.

FTP Data

The 1,876-second FTP has long served as the standard for exhaust emissions testing. Among other features, it contains elements of driving that produce start emissions as well as running emissions. In the MOBILE model revision, three FTP data sources were employed: 1) tests conducted or sponsored by EPA, most of which were performed at the EPA laboratory in Ann Arbor, Michigan; 2) data received from the American Automobile Manufacturers Association (AAMA) based on testing conducted in Michigan and Arizona; and 3) American Petroleum Institute (API) data collected in Arizona (USEPA 1999a). Vehicle model years range from 1981 through 1993, and both cars and trucks are included. Table 1 contains a cross tabulation of all the vehicles by type, model year, and technology for the three data sets combined.

Most of the data from 1990 and later model year vehicles were supplied by AAMA, while most of the pre-1990 data came from EPA laboratory testing. The API sample, 99 cars and trucks, is relatively small. Its chief appeal is that the vehicles' mileage readings, all over 100,000 miles, are generally higher than the rest of the sample. There has been a general transition from carbureted and open loop technologies in early model years to fuel injection in more recent years. Port fuel injected vehicles have represented the dominant technology since the 1990 model year. Although not directly apparent in table 1, new catalyst technology has been slowly phased into the U.S. fleet since the mid 1980s.

TABLE 1 Numbers of Vehicles by Model Year and Technology in the Combined FTP Data Set

	Cars					Trucks					
Model year	Open loop	Carbureted	TBI	PFI	Subtotal	Open loop	Carbureted	TBI	PFI	Subtotal	Total
1981	657	367	15	29	1,068	0	124	0	0	124	1,192
1982	71	71	74	8	224	0	45	0	0	45	269
1983	57	63	127	62	309	3	8	0	0	11	320
1984	30	5	46	35	116	22	26	0	1	49	165
1985	74	24	56	66	220	30	33	13	6	82	302
1986	34	7	60	92	193	9	14	23	41	87	280
1987	17	1	76	106	200	0	0	6	4	10	210
1988	15	0	69	113	197	0	0	0	0	0	197
1989	22	0	38	103	163	0	0	0	0	0	163
1990	0	0	160	250	410	0	0	144	1	145	555
1991	0	0	91	426	517	0	0	141	144	285	802
1992	0	0	57	347	404	0	0	92	92	184	588
1993	0	0	29	366	395	0	0	90	93	183	578
All years	**977**	**538**	**898**	**2,003**	**4,416**	**64**	**250**	**509**	**382**	**1,205**	**5,621**

PFI = Port fuel injected
TBI = Throttle body injected

IM 240 Data

Because FTP data can be potentially tainted with vehicle sampling (recruitment) bias, a means must be devised to account for it. One possible approach is to supplement FTP data, or adjust it, with IM 240 data. The IM 240 test cycle was developed to provide a relatively short (240-second) test that captures the essential features of the FTP. While the IM 240 test cycle is considered less representative of real world driving than the FTP, it has one clear advantage: because it is required for all vehicles in every U.S. noncompliance region, the data sets are very large and essentially free of recruitment bias. Consequently, the results of IM 240 tests provide candidate data with which to supplement FTP results (USEPA 1999b).

HR505 Data

Unfortunately, the IM 240 test only collects running emissions. Therefore, IM 240 data can only be used to adjust the running portion of FTP emissions supplied to MOBILE6. This can be accomplished using results from FTP tests that involve collecting an extra bag of emissions known as the Hot Running 505 (HR505) component (USEPA 1999c). The HR505 is an extra exhaust emissions test cycle performed immediately following collection of the conventional third bag in the standard FTP. This additional bag is a duplicate in terms of speed and time of the first and third bags. The only difference between the bags is that the HR505 does not include an engine start. For the MOBILE model revision project, a special set of 77 FTP tests were used for which the HR505 was available.

Dayton IM 240 Fast-Pass Data

Data from the Ohio I/M program include IM 240 test results on all 1981 and older registered cars and light-duty trucks scheduled to be tested from April 1996 through March 1997. Since the testing frequency in the Ohio program is biennial, this collection, which contains more than one million vehicles from three separate Ohio cities (Cleveland, Akron/Canton, and Dayton/Springfield), represents approximately half the overall population. However, only the data from Dayton/Springfield, the "Dayton data," were used in the MOBILE model revision project, and these data were further restricted to the valid initial tests; no post-repair retests were used. Only the Dayton data were used because that city never implemented any I/M or anti-tampering program (ATP). Consequently, there was reason to believe that deterioration of measured emissions would be more "natural" than in other parts of the state. The resulting data set contains IM 240 test scores for more than 180,000 cars and light-duty trucks.

An important feature of the Ohio I/M program is that it employs a "fast-pass" algorithm to speed up the testing process. Under this protocol, a vehicle's emissions are monitored in real time, and the test is terminated before completion if the accumulated emissions are sufficiently low. As a result, in order for the Dayton data set to be useful, measurements for a full 240-second cycle must eventually be constructed.

Wisconsin Full 240-Second I/M Data

A set of full 240-second I/M data were collected in Wisconsin during December 1995, April 1996, and October 1996. This data set contains observations on 3,148 cars and 1,192 light-duty trucks, with model years ranging from 1981 through 1995. Data from Wisconsin are preferable to similar data from Arizona and Colorado, the other two IM 240 states reporting second-by-second data, due to the geographic, demographic, and meteorological similarities between Ohio and Wisconsin. Recall that the Dayton IM 240 data is of interest because of its more natural state. Furthermore, both states use the same testing contractor, so analyzers and specific test procedures are likely to be similar.

FTP and IM 240 Correlation Data

Additional data are ultimately required to determine the correlation between IM 240 and FTP emissions measurements. The data available for this purpose consist of 938 FTP and IM 240 paired tests conducted on vehicles chosen from I/M lanes in Hammond, Indiana and Phoenix, Arizona. Vehicles were randomly selected at the inspection lanes to be included in this program, and IM 240 tests were conducted using the fuel resident in their tanks. The vehicles were then moved to the lab, and each vehicle's fuel was replaced with Indolene, in accordance with standard test protocol. An FTP test was then conducted, as was another in-lab IM 240. Only the IM 240 tests on tank fuel are of interest since the IM 240 data from Ohio derive from tank fuel tests. Again note that it is the Dayton IM 240 that is of specific interest to the MOBILE model revision project.

FTP ADJUSTMENT METHODOLOGY

Historically, the MOBILE model has portrayed vehicle exhaust emissions as a piecewise linear function of accumulated mileage. Different functions are used for the three pollutants, hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_X), and for different vehicle categories defined by model year and engine technology. This approach has been retained in MOBILE6 for the modeling of running emissions. A somewhat different concept underlies the modeling of start emissions, where vehicles are assumed to fall into discrete categories of "normal" and "high" emitters. The adjustment for possible bias in FTP data employs a series of regression analyses that enable the use of IM 240 tests to model the deterioration of FTP values. Figure 1 contains a flowchart depicting how the various data sources are combined and how the FTP results are eventually adjusted.

Model Year and Vehicle Categories

Individual deterioration functions were developed for subsets of vehicles classified by vehicle type, model year, and fuel metering technology. The categories in table 2 were determined largely on the basis of engineering judgement. To a great extent, model year serves as a proxy for technology advances. The choice of model year groupings also approximately reflects the continued tightening of regulatory emission standards.

For a particular model year/technology class, MOBILE5 included an upward turning "kink" in the basic emission rate (BER) function at 50,000 miles; that is, emissions are expected to deteriorate at a faster rate beyond 50,000 accumulated miles (USEPA 1994). As already described, a great deal of additional data were available from tests on newer model vehicles for use in the development of MOBILE6. This permitted a closer examination of the appropriateness of the 50K kink and led to its eventual elimination as an explanatory factor.

Separating Start and Running Emissions

Emissions on the FTP are computed by weighting the gram per mile measurements from the three bags of the test cycle. The formula for this calculation is:

$$\text{FTP} = 0.21 \times (\text{bag } 1) + 0.52 \times (\text{bag } 2) + 0.27 \times (\text{bag } 3) \quad (1)$$

The weights equal the fractions of vehicle-miles traveled in the three modes of driving captured by the cycle. Bags one and two constitute the "LA4" cycle, which refers to the underlying driving data collected in Los Angeles. This leads to formulas for the calculation of running and start emissions using the bag measurements from an FTP.

For a given FTP test, running emissions are determined by a linear function of bag two emissions and HR505 emissions. The result is labeled "Running LA4" since it captures emissions for the LA4 cycle with start emissions removed. The general form of this function is given by:

$$\text{Running LA4 emissions (grams/mile)} = 0.48 \times (\text{FTP bag } 2) + 0.52 \times \text{HR505} \quad (2)$$

The HR505 values are themselves estimated from emissions measurements associated with bags one to three using a regression model developed from the special 77-car HR505 data set. In this way, it is possible to compute running emissions for each of the FTP tests in the EPA/Industry database.

Likewise, start emissions for each FTP test are determined by a linear function of HR505 and the start emissions components of bags one and three. The general form of this expression is:

$$\text{Start emissions (grams)} = 0.21 \times (\text{FTP bag } 1) + 0.27 \times (\text{FTP bag } 3) - 0.48 \times \text{HR505} \quad (3)$$

HR505 values are the same ones used in determining running emissions.

Modeling Running Emissions

For running emissions, several functional forms were studied before selecting a piecewise linear model in which emissions are constant at lower mileages and increase after about 20,000 miles. The 20,000-mile point was selected subjectively following graphical

FIGURE 1 Overview of Methodology to Estimate Running and Start Basic Emission Rates

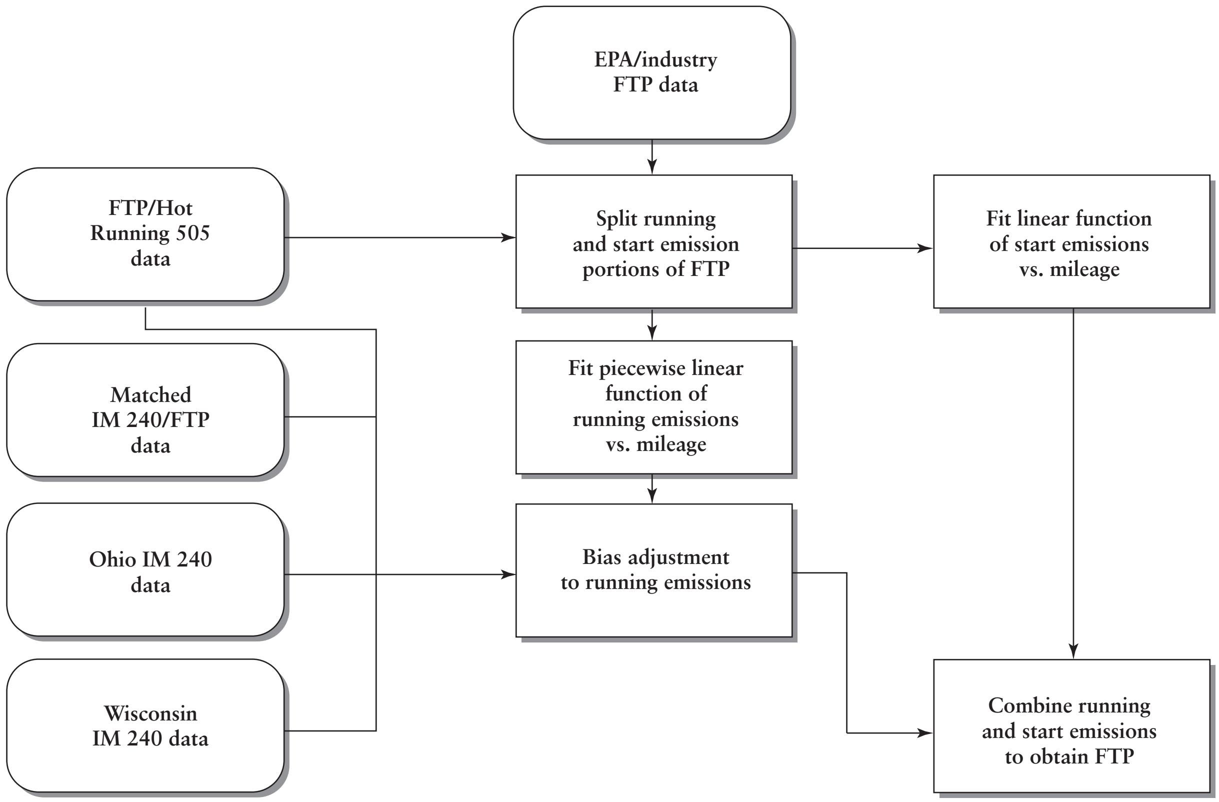


TABLE 2 Model Year and Technology Categories Used in MOBILE6 to Model 1981 to 1993 Light-Duty Vehicles

Model years	Technology
Cars	
1988–93	Port fuel injected (PFI)
1988–93	Throttle body injected (TBI)
1983–87	Fuel injected (PFI and TBI)
1986–93	Closed loop carbureted/open loop
1983–85	Closed loop carbureted/open loop
1981–82	Fuel injected (PFI and TBI)
1981–82	Closed loop carbureted/open loop
Trucks	
1988–93	Port fuel injected (PFI)
1988–93	Throttle body injected (TBI)
1984–93	Closed loop carbureted/open loop
1981–87	Fuel injected (PFI and TBI)
1981–83	Closed loop carbureted/open loop

"Open loop" refers to vehicles which do not use electronic feedback systems to control the delivery of fuel to the engine cylinders. Most current light-duty vehicles make use of feedback, or "closed loop," systems.

inspection of regression lines estimated from the available data. This approach was adopted after observing that simple linear regressions produced unrealistic fits of emissions at low mileage. This is attributed to a shortage of low-mileage FTP observations.

Modeling Start Emissions

With the start component of emissions, it was assumed that there are two categories of vehicles: "normal" and "high" emitters. This distinction facilitates the treatment of inspection and maintenance credits in MOBILE. A vehicle was assigned to its emitter class for a given pollutant depending on whether or not its FTP emissions exceeded an arbitrary multiple of its regulated emissions standard. For HC and NO_x, this multiple was chosen as two, while for CO it was three.

Following this classification, HC and CO deterioration in normal emitters was modeled as a simple linear function of mileage using least squares regression. For these pollutants, the high emitters were found to be uncorrelated with mileage, so they were taken to have constant emissions equal to the sample mean. At a given mileage, the normal and high values were combined in a weighted average, with the weights equal to the fractions of normal and high emitters associated with that mileage level. For NO_x emissions, the emitter class distinction was not used for modeling deterioration. A simple linear function of mileage was fitted using least squares regression.

Adjustment for Possible Bias

The adjustment for possible bias was based on the Dayton I/M data. It only applies to the Running LA4 equation since the IM 240 cycle does not contain an engine start. The adjustment was achieved through a series of steps that involved transforming fast-pass IM 240 scores into running FTP emissions. In the first step, a regression model was fitted to the Wisconsin full 240-second I/M data to predict full 240-second values from fast-pass scores. Separate models were determined for each pollutant.

Next, the matched IM 240 and FTP measurements from Indiana and Arizona were used to construct a full suite of running emissions from IM 240 measurements. This first required the use of the equation for Running LA4 emissions to compute a running emissions value for each FTP test. A separate regression equation derived from the matched pairs was then used to predict running emissions from each IM 240 measurement.

Finally, this model was applied to the Ohio IM 240 values to obtain running emissions estimates for each of the points in that large database. Associated with each of these values is a vehicle odometer reading and model year. However, the Dayton IM 240 data suffered from a problem with unreliable odometer readings. After an attempt to correct the data, it was decided to circumvent the problem by replacing the recorded mileage with average accumulated mileages from national vehicle travel surveys (Oak Ridge National Lab 1995). For each vehicle in the Ohio IM 240 data set, the model year and technology were identified and the corresponding average mileage was assigned. Then, average running emissions were computed for each model year and technology class. The emissions averages were then compared to the running emissions estimated from the piecewise linear functions at the appropriate mileages. This produced several differences in each of the model year/technology groups shown in table 2. Within each of these groups, the differences were smoothed using simple regression analysis, yielding additive adjustment factors equaling zero at mileage zero and changing linearly with mileage. Most of the adjustments are in the direction of increased emissions.

RESULTS

Figure 2 (a-c) illustrates the effect on running emissions of the bias adjustment for 1988-93 port fuel injected (PFI) cars. Running and start emissions can be reconstituted as a complete FTP estimate. Similar graphs for earlier model years are found in USEPA (1999a). The equation coefficients underlying these graphs, a part of the MOBILE6 computer code, also appear in that report.

Start emission estimates are reported in USEPA (1999d). The split between normal and high emitting vehicles described earlier enables the calculation of a fraction of high emitters at any mileage. This fraction increases with accumulated mileage. For the purpose of comparing MOBILE6 to MOBILE5, a composite of running and start emissions can be calculated to produce FTP estimates for the new model. The equation for this calculation is the simple linear function:

$$\text{FTP} = (7.5 \times \text{running} + 0.521 \times \text{start}) \div 7.5 \quad (4)$$

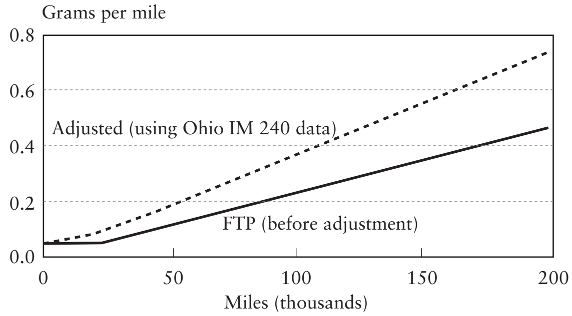
The constant 7.5 derives from the fact that in the LA4 cycle the total distance driven during the collection of bags 1 and 2 is 7.5 miles. Figure 3 (a–c) depicts MOBILE FTP HC deterioration functions for model years 1992, 1987, and 1981 fuel injected cars and compares the MOBILE5 kinked line to the proposed MOBILE6 line. This pattern is typical. For recent model years, MOBILE6 predicts emissions with considerably less deterioration than the earlier version whereas in older model years these differences are less pronounced.

Other Model Years

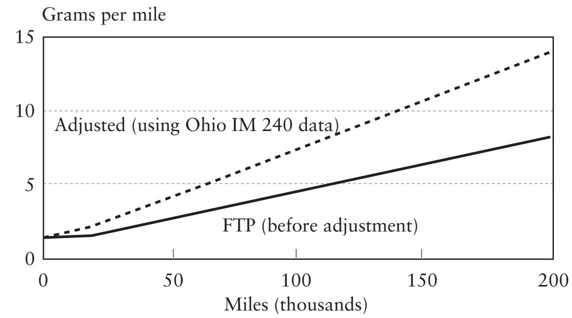
The equations used in MOBILE5 provided the basis for the modeling of pre-1981 open loop vehicles in MOBILE6. In the new version of the model, it is necessary to estimate the start and running

FIGURE 2 Running LA4 Emissions for 1998–1993 PFI Cars

2(a) Hydrocarbons (HC)



2(b) Carbon monoxide (CO)



2(c) Oxides of nitrogen (NO_x)

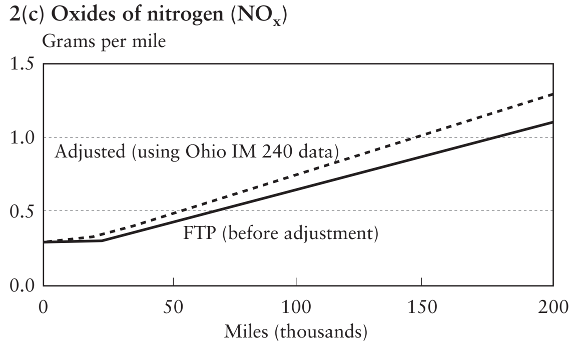
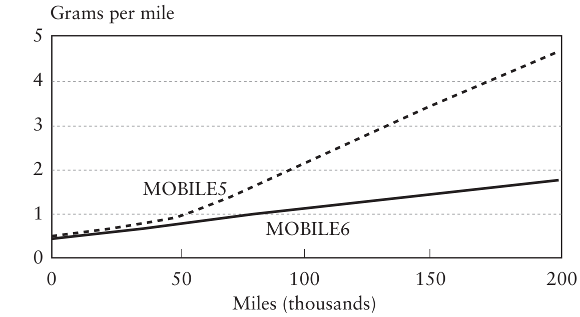
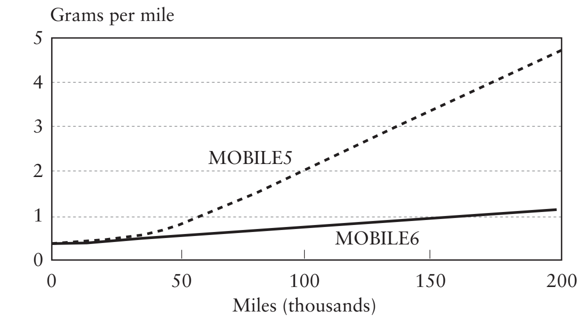


FIGURE 3 FTP Comparison of MOBILE5 and Proposed MOBILE6 Hydrocarbon (HC) Emission Factors

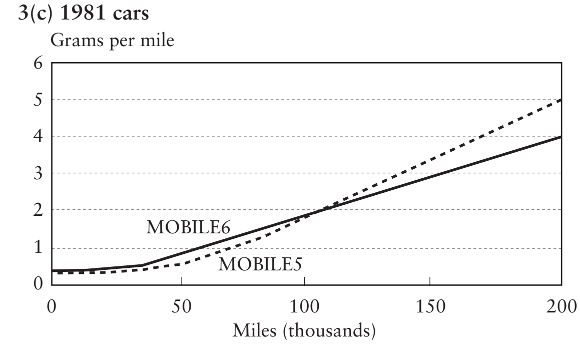
3(a) 1992 cars



3(b) 1987 cars



3(c) 1981 cars



components of the FTP. This was accomplished by computing start and running emission fractions using the FTP data underlying the MOBILE5 deterioration functions together with the results of the 77-test HR505 data analysis (USEPA 1999e).

For model years 1994 and later, exhaust emissions deterioration is influenced by new regulations, including the introduction of On-Board Diagnostics (OBD) and enhanced I/M programs. Data with which to model deterioration in these vehicles were not available in sufficient quantity for use in the model revision project. In MOBILE6, these changes are modeled by assuming that emissions are reduced from earlier model-year levels in proportion to the tightening of standards for these newer vehicles (USEPA 1999f; USEPA 1999g).

Statistical Uncertainty

For the various regression analyses described above, goodness-of-fit, as measured by R^2, is superficially encouraging. For example, in the key regression models of running emissions and start emissions, R^2 values range from 0.922 to 0.953 for the three pollutants. Due to the natural skewness found in emissions data, log transformations were sometimes applied to emissions test values prior to fitting regression equations, a process which tends to produce higher R^2 values than with untransformed data. The EPA reports cited here include values of R^2 and other standard measures of goodness-of-fit for the various estimated models. When the equations are combined using the steps summarized in figure 1, overall confidence in the model coefficients is undoubtedly reduced.

CONCLUSIONS AND RECOMMENDATIONS

The MOBILE model is an important tool for planning and implementing air quality management. The changes to the model described in this paper have significant implications for decisionmakers responsible for developing programs of emissions control. In particular, the reduced rates of emissions factor deterioration in newer vehicles could lead to a re-evaluation of control strategies in areas not in attainment with federal standards.

The MOBILE6 emissions inventory model includes some important modifications to earlier versions of the model. When separated into running and start components, the estimation of deterioration in basic emission rates poses a difficult challenge. The work described in this paper represents EPA's current approach to addressing that challenge.

Given the nature of available data, modeling deterioration of vehicle exhaust emissions requires considerable judgement and experience. For the purpose of the MOBILE model, there is also a strong incentive to apply simple, easily understood statistical methodologies. These principles guided the model construction described in this paper, despite the apparent complexity of the overall scheme. As noted earlier, the more complete measurement of confidence in the final basic emission rate (BER) equations would be a worthwhile undertaking.

The shortcomings of the data used in this work underscore the need for better test program design and data measurement. Emissions testing is expensive, and frequently it is not possible to obtain data according to the requirements of good experimental design. A large dataset, like that obtained from a state I/M program, does not guarantee satisfactory results in the absence of other desired statistical criteria. Many of these concerns would be reduced with closer collaboration between practitioners in the fields of emissions testing and emissions modeling, and EPA is currently instituting programs toward that end.

The state of California maintains a parallel emissions modeling program designed to support its somewhat more stringent air quality regulations. The On-Road Emissions Inventory Estimation Model (EMFAC) is similar in many ways to MOBILE, and there is a high degree of coordination between the California and EPA modeling efforts. Nevertheless, there are substantial differences between the two models in terms of underlying data, assumptions, and methodology. Comparing predictions generated by these models would be a challenging but useful exercise.

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